Throughput and Delay Performance of Mobile Internet Applications Using LEO Satellite Access

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ABSTRACT

Low Earth Orbit (LEO) satellites are an essential complement of the cellular radio infrastructure, especially the Universal Mobile Telecommunications System (UMTS), for mobile (pedestrian and, more important, vehicular) access to the Internet in sparsely populated areas, where high bandwidth UMTS cells cannot be economically deployed. LEO users would eventually switch between the satellite segment and the terrestrial one depending on the environment in which they are located. In this paper we analyze various mobile Internet applications in representative urban scenarios for two existing LEO systems. To this end, we develop a LEO channel propagation model that includes shadowing from surrounding building skylines, based on actual data in a built-up area. We consider "single satellite hop" transmissions from the mobile terminal to the satellite gateway. For this scenario, we compute via simulation the performance for FTP and HTTP applications as perceived by mobile users traveling at varying speeds along "urban canyons". We then consider a multi-hop satellite path between remote urban locations and evaluate the performance of delay sensitive applications. We also evaluate the performance of various TCP versions (Tahoe, Reno, SACK) in different presence of packet loss.

I. INTRODUCTION

Mobile access to the Internet is bound to become extremely popular very soon. This is mainly because users already begin to depend on the Internet for many activities of their daily routine (business, entertainment, education, family, shopping etc), and naturally wish to extend connectivity while they are moving. "Nomadic" Internet users are supported in their quest for efficient, mobile access by a myriad of new networking technologies, from the Universal Mobile Telecommunication System/International Mobile Telecommunications 2000 (UMTS/IMT2000) to Wireless LANs, Metricom and Bluetooth. One technology that can be proposed very effectively for mobile Internet applications is the satellite technology.

The satellite technology is already well mature to take on the new mobile Internet challenge. In this process each satellite is an element of a packet network, and new design problems arise both at the network and the transport layers. The concept of network, or better, "constellation" is at the heart of the Low Earth Orbit (LEO) satellites. LEOs can be considered a valid complement for mobile access to the Internet. One key requirement in the development of mobile Internet strategies will be to determine how well can a LEO infrastructure support the broad variety of mobile Internet applications in a broad range of environments, including the urban environment.

TCP is probably the most critical building block in the support of Internet applications and is a widely accepted standard for reliable data transport within terrestrial wired networks on top the Internet Protocol (IP). Due to the increasing interest of fixed and mobile interactive service delivery via satellite directly to the final user, many studies on the TCP/IP are focused to overcoming TCP limitations within the satellite medium, as well as to allowing its efficient use in hybrid terrestrial/satellite networks [1-9]. This is particularly significant in the frame of the UMTS scenario that intends to merge the attributes of personal/mobile and multimedia communications at a worldwide scale [10]. Until now TCP has been deeply studied with reference to the use of Geostationary Earth Orbit (GEO) satellites [1-6]. Interest is increasing for data transmission via LEO constellations, and only a few works have been presented in the literature yet [7-9].

The main goal of this paper is to evaluate the performance of various mobile Internet applications in representative LEO scenarios, considering two existing constellations (Iridium [11] and Globalstar [12]). Our results are based on a LEO channel propagation model that includes shadowing from surrounding building skylines. The model parameters are based on actual data in a built-up area.

The paper is organized as follows. Section II reviews the LEO system environment and the characteristics likely to impact TCP and more generally Internet applications. Section III describes the "urban canyon" model for the study of the LEO channel in urban environments. Section IV presents Network Simulator-2 (NS-2), the simulation platform used in our experiments and describes the extensions required for LEO experiment support. Section V and Section VI present simulation scenario and the experimental results, respectively. Finally conclusions are drawn.

II. SATELLITE ENVIRONMENT AND TCP

Next generation mobile communication systems will be characterized by an enhanced set of services, comparable to those offered by fixed networks. They will also extend the coverage of the second generation systems by implementing an infrastructure in which the satellite component will be perfectly integrated with the terrestrial one.

UMTS/IMT2000 will be the platform for new multimedia services. In the new system implementation, the satellite component is intended to be perfectly integrated with the terrestrial component [10]. In this scenario the satellite assumes a particularly important role, not only complementary to the terrestrial component, especially if aiming at seamless roaming and fully global coverage, ensuring access also to maritime, aeronautical and remote users.

A. Satellite features impacting Internet application performance

In new generations, each satellite is a switching node of a satellite constellation network. The constellation network is a full fledged packet network and can thus be operated with existing packet network protocols (e.g., routing, congestion control, QoS support, etc).

First, when considering the performance of TCP as well as real time (e.g., voice) applications one must account for the large propagation delays [1]. The problem is particularly acute in TCP applications over links with large delay × bandwidth (DBP) products, where a large TCP window is required for efficient use of the satellite link. A lossy satellite link can cause frequent "slow start" events, with a significant impact on throughput. In real time applications (e.g., voice and video) supported by UDP, rather than TCP, the large delay is also a problem, although in a different way than for TCP. The delay problem is further aggravated, in the case of LEO networks, by the fact that the delay varies as LEOs move along their orbits. In fact, the constellation geometry changes during the life of a connection. Satellite and/or gateway handovers will also occur, causing temporary interruptions in the stream. The key satellite network features that need to be considered in order to evaluate the impact of satellite on internet application performance are: propagation delay**,** DBP, frequent handover, signal-to-noise ratio (SNR), satellite diversity, routing strategy.

B. TCP enhancements for satellite networks

TCP is a connection-oriented protocol designed to allow reliable transport of data in any communication media, including satellites. However, some of the TCP features are significant in assessing throughput performance when a TCP connection involves a satellite network.

Much of the previous research regarding TCP over satellite links focuses upon modification to the basic Error Control (EC) and Flow Control (FC) strategies to improve performance over satellite links [13-19].

In the design and development of new TCP applications on LEO and GEO systems it is important to carefully assess the performance of various "TCP enhancements" in the specific context of the satellite constellation and application scenario. Generic enhancements may have a counterproductive effect on performance. In a later section we will evaluate different TCP schemes for representative LEO scenarios.

III. LAND MOBILE SATELLITE CHANNEL MODEL

In this paper we use a physical-statistical land mobile satellite channel model. The model is based on computing the geometrical projection of buildings surrounding the mobile, described through their height and width statistical distributions [20, 21]. The existence or absence of the direct ray defines the line-of-sight (LOS) state or shadowed state, respectively. The modeling effort can be divided in two parts:

1. *Deterministic or statistical parameterization of urban environment* - The physical-statistical approach used here proposes a canonical geometry for the environment traversed by a mobile receiver. The canyon street composed of buildings on both sides will block or not block the satellite link along the mobile route depending on the satellite elevation. In order to address also the statistical approach, which enables us to compute synthetic canyon streets, we have investigated urban canyon street geometry and have parameterized real street canyons. The statistical approach is clearly of interest towards general results provided that we use real data to generate the canyon streets. In addition, statistical approaches are generally less time consuming and Building Data Base (BDB) are not always available.
2. *Calculation of the skyline elevation angles (masking angles)* - Once the canyon shaped street data is available, either by extracting it from BDBs or by computing it, the elevation angle to the skyline is computed. At every user

position along the mobile route (mobile user) a scan of 360 degrees is performed to compute the elevation angle to the skyline, i.e. the elevation masking angle is computed for every azimuth angle around the user terminal.

IV. SIMULATION PLATFORM AND EXTENSIONS FOR SATELLITE SUPPORT

The simulations have been performed using NS-2 [22], enhanced to provide better support for satellite environments according to the following issues:

a) *Terminal Mobility and Shadowing Channel* – A shadowing channel was added to simulate the behavior of a terminal in an urban environment. The channel is derived from the skyline of a street and the terminal is shadowed if the elevation angle of the satellite is less than the elevation of the skyline, as explained in Section III. The channel has an ON-OFF behavior and the link is assumed to be down when the terminal is shadowed. Also, mobility was added to the terminal by moving it up and down the street. The skyline seen by the terminal changes as it moves and this combined with the current position of the satellite network determines the shadowing state of the terminal.

b) *Gateway* – The concept of a "Gateway" node was added to the simulator. This node was introduced to model the "Gateways" as present in satellite networks like Iridium and Globalstar. The Gateway can be used as an interface between the satellite constellation and a terrestrial network and this feature can be used to model hybrid satellite-terrestrial networks. An important feature of the Gateway node is that it maintains links to all satellites that are visible to it. Also, these links typically belong to different orbits in a non-polar constellation. This "multiple links" property is used to enhance the Globalstar system to a "full virtual constellation". Namely, connections between satellites in different orbits are set up through the Gateway node.

c) *Mobility Modeling and Handoff* - In the simulations, mobility is modeled by moving the terminal continuously up and down the street over a straight path of about 10 km. The considered terminal speeds are 0 m/s (fixed terminal), and 2 m/s (pedestrian). The position of the terminal at any time is determined by its speed and the elapsed time. The skyline seen by the terminal at that position gives a minimum elevation angle below which a satellite is shadowed. While modeling handoffs, we assume that the handoff execution time is negligible. The handoff procedure is invoked every 0.4 s and a handoff takes place when the current satellite is shadowed by the skyline or goes below the horizon. While performing the handoff, we look for the "unshadowed" satellite with the highest elevation angle. Note that the skyline gives us the minimum elevation angle above which a satellite is visible for a certain value of azimuth of the satellite. Thus, the azimuth of a satellite together with the information provided by the skyline determines whether a satellite is shadowed or not.

V. SIMULATION SCENARIOS

Considering all the possible options of satellite configurations, service and application types, channel behavior and protocol parameters, the number of possible scenarios becomes clearly unmanageable. Hence, we have selected a set of most representative scenarios for evaluation. The different options will be described in detail in the following subsections. Common input parameters for the simulations are TCP packet size = 1000 bytes, and the bit rate = 144 kbit/s (corresponding to the S-UMTS target bit rate, [10]), unless otherwise indicated.

A. LEO satellite scenarios

Our simulations were performed in two LEO satellite scenarios:

- *"single-hop"* - a terminal is connected to the Gateway by one satellite.
- *"full satellite network"* - two terminals communicate using a LEO satellite constellation that provides connectivity between any two points on Earth laying within the coverage area.

The former scenario can be representative of a satellite network configuration not equipped with ISL or of a connection required in the service area of a single satellite. In the single-hop scenario all the traffic is transferred between the user terminal and the Gateway through one satellite. Thus, the user terminal and the Gateway see the same satellite. In our experiments, the user terminal is located in Madrid (40° N and 4° E) and the Gateway is located in France (47° N and 1° W).

The latter scenario needs to have features such as routing on the satellite and requires satellites to be of the regenerative type. Moreover, such satellite constellations would typically be able to connect any points on the Earth without making use of the terrestrial network.

For the purposes of this paper, we evaluated Iridium-like and Globalstar-like LEO constellations. Iridium is an example of a polar constellation and Globalstar of a non-polar constellation.

B. Traffic model

We performed simulations for various services for both Iridium and Globalstar. We modeled different some Internet services as explained below:

1. *HTTP* – HTPP is modeled as per the models described in [23] and [24]. The former refers to a unit of HTTP transfer as a Session. A Session in our model consists of 5 pages, of 5 kbytes each (actually 50 packets of 1 kbytes each). The delay between the completion of one page transfer and the start of the next one is 40 s; this is referred to as the "viewing time" of a page.
2. *FTP* – In the FTP model, files of fixed size are transferred in order to get delay statistics, while a fixed-duration FTP transfer is performed to get throughput results.

C. Channel options

In our experiments, two different channel options were considered

1. Constant PER but no shadowing impairments. Lossy terminal-to-satellite link were introduced in ns-2 to get performance for different TCP version in a real LEO satellite scenario.
2. Occurrence of shadowing impairments for mobile user according to the canyon street model described in Section III. A street of Madrid presenting 30° of average elevation masking angle has been used. The street is about 10 km long and the width is 20 m. The terminal is located in the middle of the street and is moving up and down it.

D. Evaluated parameters

To evaluate the performance of satellite configurations using TCP, throughput and delay have been identified as the most meaningful parameters.

VI. SIMULATION RESULT

A. Single Hop - FTP – Constant PER and no shadowing effect

In the first set of simulations, we ran FTP (with unlimited data) over different TCP versions (Tahoe, Reno and SACK) for fixed time intervals to get results for the throughput achieved using Iridium and Globalstar. FTP connections with a 15-minute duration were run every 30 minutes. We ran 24 such connections (representing 12 hours of simulation time) and the throughput results were averaged over all connections. The channel has been assumed to have a constant PER (Packet Error Rate) on the mobile terminal-to-satellite link. Table 1 shows the throughput achieved for different PERs for TCP Tahoe, Reno and SACK respectively.

As seen from Table 1, there is a very little difference between the throughputs achieved by TCP over Globalstar or Iridium. Moreover, the throughputs achieved by different TCP versions are very similar. This behavior can be easily explained by recalling that round trip delay is less than 100 ms, channel rate is 144 kbit/s and packet size is 1000 bytes. In these conditions, the optimal TCP window (to keep the "pipe full") is W = 2.

	Iridium			***Globalstar***		
PER	**Tahoe**	**Reno**	**SACK**	**Tahoe**	**Reno**	**SACK**
10^{-4}	0.895	0.893	0.892	0.892	0.890	0.890
10^{-3}	0.892	0.890	0.892	0.888	0.887	0.888
10^{-2}	0.858	0.864	0.878	0.853	0.859	0.875
10^{-1}	0.341	0.334	0.357	0.327	0.334	0.347

Table 1 - Bandwidth utilization for different TCP versions and satellite constellations in a single-hop scenario over constant Packet Error Rate (PER) channel link.

The reader can verify that, by virtue of small window and small propagation delay, the well known advantages of the TCP enhanced versions Reno and SACK (which do not drop to slow start and perform fast, selective retransmissions) have absolutely no effect in this case. For this reason, we did not extend our investigation to other TCP versions such as TCP West and TCP ECN. The reader should be aware, however, that in future LEO satellite systems offering broadband services (say several Mbit/s to the mobile terminal) the choice of TCP protocol will make a difference.

B. Single Hop - HTTP with shadowed channel and mobile terminal

We also performed simulations for HTTP transfer over TCP Tahoe for Globalstar constellation to get a comparative analysis between an ideal channel and the mobile channel. We ran 1000 HTTP sessions (as described in Section V), with the interval between two sessions being 20 minutes. "Page delay" (associated with a single HTTP page) and "Session delay" (associated with the transfer of all pages in a session) have been evaluated. The simulations were performed for a channel not affected by any PER but with a terminal speed of 2 m/s both in shadowed and unshadowed conditions. The page and session delay complementary cumulative distributions for HTTP transfers are shown in Figures 1 and 2 respectively.

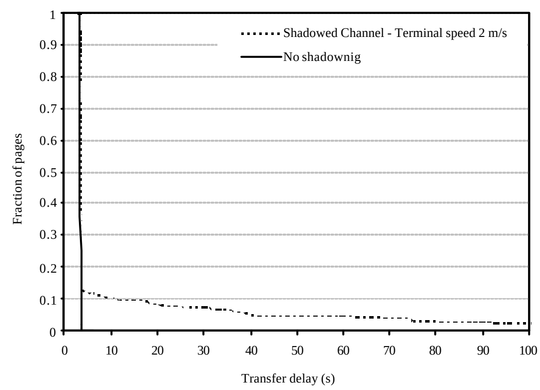

Figure 1 - HTTP page delay transfer complementary cumulative distribution.

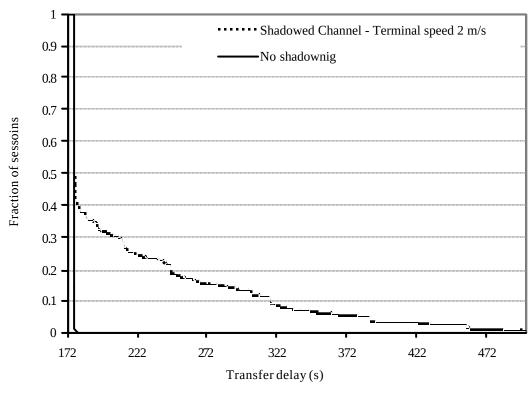

Figure 2 - HTTP session delay transfer complementary cumulative distribution.

In both figures the curve relative to the unshadowed case performs like a unit step highlighting the occurrence of a constant delay. Figure 1 shows that the delay variance for retrieving one page is extremely large. However, from Figure 2, we note that the variance of the HTTP session delay is much smaller, and indeed manageable. In essence, the pedestrian user inspects the page (for up to 40 s) and is unaware of the shadowing, until he requests the next page. The shadowing dead times are utilized for local inspection of the pages.

C. Full Satellite Network - FTP – Constant PER and no shadowing effect

In the last set of experiments, we ran FTP (with unlimited data) over different TCP versions (Tahoe and SACK) between a Gateway located in Rome (42° N and 12° E) and a terminal in Los Angeles (33° N and 118° W) in full satellite networks.

We consider Iridium-like constellation and Globalstar-like constellation, which is suitably evolved to be able to provide connectivity between two terminals in their coverage area without relying on the terrestrial network. Each satellite in the Iridium-like constellation has 4 inter-satellite links, i.e., 2 inter-plane links connecting to the previous and the next in the same orbit and 2 intra-plane links connecting to the corresponding satellite in the adjacent orbits. Also, in a polar constellation like Iridium, there are 2 regions in which the planes are counter-rotating, thus forming a "seam" in the topology. We consider the Iridium-like constellation both with and without cross-seam links. While considering Iridium without cross-seam links, some satellites may have only one inter-plane link. In the enhanced Globalstar-like constellation, intra-plane links are introduced connecting each satellite to the previous and next satellites in the same orbit. In addition, a number of Gateways are introduced to provide inter-plane connectivity. The Gateways can see satellites of more than one orbit and will forward packets coming from one orbit to some other, if required. There are 14 such Gateways placed at various positions on the Earth as shown in Table 2. The routing used for the networks was of the shortest path kind.

Figure 3 shows the throughput achieved vs. the PER (only for the terminal-to-satellite link) using Iridium without cross-seam links and Globalstar. FTP connections with a 15-minute duration were run every 30 minutes. We ran 24 such connections (representing 12 hours of simulation time) and averaged the throughput results over all connections.

As seen from Figure 3, the Iridium constellation has a higher throughput than Globalstar, due to lower delays. We also note that TCP-SACK performs better than Tahoe for 10^{-2} PER. It is interesting to compare the constellation (multi-hop) results with the corresponding single hop results in Table 1. For 10^{-1} PER, the single hop channel utilization is 0.87 for SACK and 0.86 for Tahoe, virtually identical. We attributed this to the small bandwidth x propagation product.

Region	GW latitude	GW longitude
Europe	47.0° N	1.0° E
	42.0° N	13.0° E
	52.0° N	45.0° E
North America	45.0° N	75.0° W
	30.0° N	95.0° W
	20.0° N	70.0° W
South America	5.0° S	95.0° W
	30.0° S	65.0° W
	8.0° S	40.0° W
South Africa	28.0° S	20.0° E
Middle East	25.0° N	45.0° E
Asia	52.0° N	80.0° E
	43.0° N	125.0° E
Australia	18.0° S	138.0° E

Table 2 – Globalstar Gateway (GW) location for full satellite network simulations.

In the multihop case (Iridium without cross-links) the propagation has now increased substantially, up to 0.25 s. Thus, the optimal window is in the order of 10 packets. TCP SACK in this scenario can make a difference. In fact, it improves Iridium TCP Tahoe performance from 0.74 to 0.83.

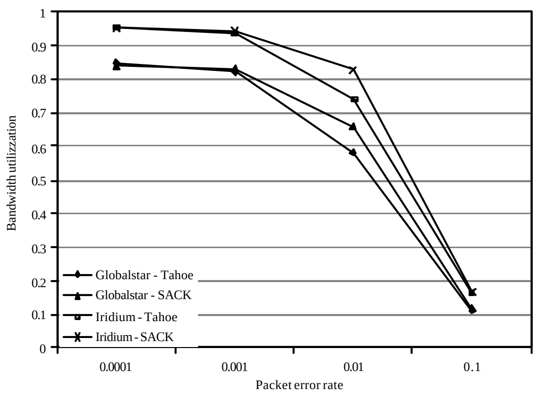

Figure 3 - Bandwidth utilization vs. throughput for TCP Tahoe and SACK and in different satellite constellation

CONCLUSIONS

In this paper we have evaluated the performance of various mobile Internet applications in two representative LEO constellation architectures: Iridium and Globalstar. We consider various traffic scenarios and a LEO channel propagation model that includes shadowing.

In the "single satellite hop" scenario we compute the throughput delivered by FTP under a channel with different PERs. It is seen that there is a very little difference between the throughput values achieved by means of TCP over Globalstar or Iridium owing to the small round trip delays. Then, we evaluated the performance of HTTP delivery to mobile users traveling along “urban canyons” in the case of Globalstar. The results show that performance is affected by the mobile speed. It is seen that there is a larger variance in HTTP delays in case the terminal is mobile.

Then we considered a multihop satellite path between remote locations in a full satellite environment and evaluated the performance of TCP in the LEO environment with lossy links (as caused by weather conditions, say). It is seen that the Iridium constellation has a higher throughput than the Globalstar constellation, due to lower delays. Also, TCP SACK performs better than TCP Tahoe, particularly, for higher packet error ratios.

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